# FLEXURAL STRENGTH AND DUCTILITY OF RC BRIDGE COLUMNS UNDER BILATERAL EXCITATION

Kazuhiko Kawashima[1], Gakuho Watanabe[2],Hidenori Ogimoto[3] and Ryoji Hayakawa[3]

[1] Professor, Department of Civil Engineering, Tokyo Institute of Technology,
[2] Research Associate, Department of Civil Engineering, Tokyo Institute of Technology,
[3] Graduate Students, Department of Civil Engineering, Tokyo Institute of Technology,

## ABSTRACT

This paper presents the effect of bilateral excitation of cantilevered reinforced concrete bridge columns with square section. Hybrid loading test and cyclic loading tests were conducted for eleven 1.35 m tall reinforced concrete columns with a 400 mm x 400 mm section. Both unilateral and bilateral excitation were imposed to the columns. Fiber element analysis was conducted to correlate the test results. It is found from the experiments and analysis that flexural strength and ductility capacity of reinforced concrete columns significantly deteriorate under the bilateral excitation than the unilateral excitation in both cyclic and hybrid loading tests.

## INTRODUCTION

The combination of two lateral components of seismic effect has been a major concern in seismic design of bridges. It is obvious that during an earthquake a bridge is subjected to a set of three components of ground motions. In practice, it is general to size bridge columns assuming that they are subjected to two lateral components in the weak and strong axes independently. Flexural strength and ductility capacity of a column are generally determined based on experimental data of cyclic loading test under unilateral excitation. Since it has been revealed that flexural strength and ductility capacity under bilateral excitation are less than those under unilateral excitation (Zahn et al 1983, Kawashima et al 1992), it is likely that the current design flexural strength and ductility capacities are overestimated

This paper presents cyclic and hybrid loading tests on eleven reinforced concrete specimens with the same structural properties to clarify the effect of bilateral excitation. Accuracy of the fiber element analysis which includes a new empirical stress vs. strain relation of confined concrete is verified based on the test data.

## EXPERIMENTAL SETUP

### Experimental Models

Eleven cantilevered reinforced concrete columns with the same structural properties as shown in Table 1 were constructed. As shown in Fig. 1, they have a 400 mm x 400 mm square section, and are 1,750 mm tall with an effective column height of 1,350 mm. They were designed in accordance with the 1996 Japanese Design Specifications of Highway

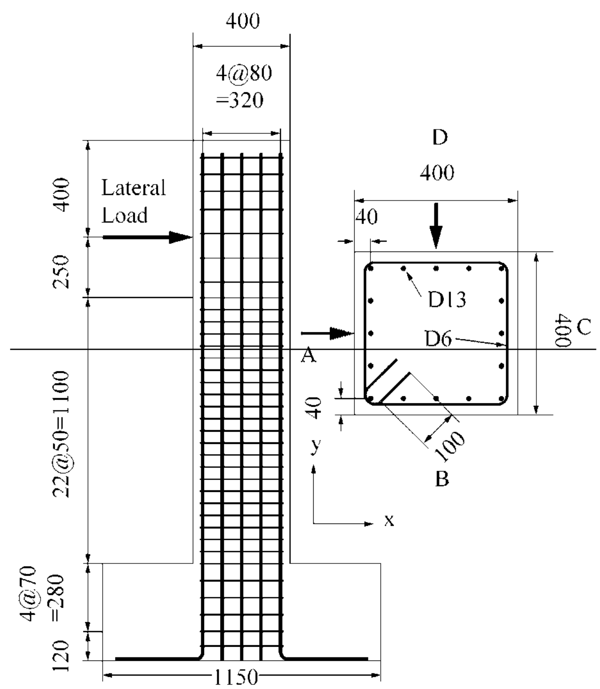
Table 1 Test Cases

(a) Cyclic Loading Tests

| Specimens | Concrete Strength (MPa) | Loading Orbits |
|---|---|---|
| C-1 | 28.2 | Unilateral |
| C-2 | 28.0 | Diagonal |
| C-3 | 28.6 | Square |
| C-4 | 26.4 | Circular |
| C-5 | 26.7 | Ellipsis |

(b) Hybrid Loading Tests

| Specimens | Concrete Strength (MPa) | Direction of Excitation | Ground Motions |
|---|---|---|---|
| P-1 | 28.68 | Unilateral | Kobe 30% |
| P-2 | 25.43 | Bilateral | |
| P-3 | 27.16 | Unilateral | Kobe 40% |
| P-4 | 26.93 | Bilateral | |
| P-5 | 31.17 | Unilateral | Sylmar 50% |
| P-6 | 34.23 | Bilateral | |




(a) Side

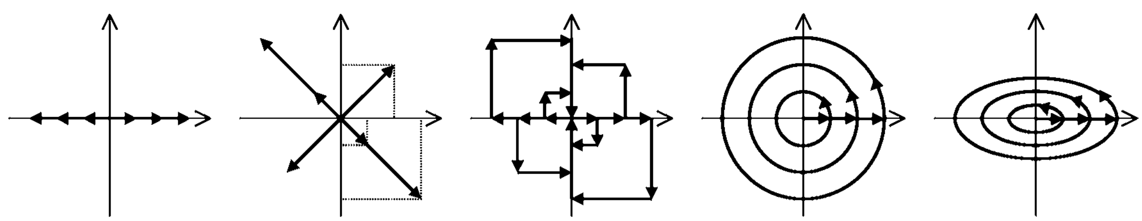
Fig.1 Models

Bridges so that they fails in flexure using the Type-I (middle-field) and Type-II (near-field) ground motions at a site corresponding to the moderate ground condition (Type-II Ground Condition) (Japan Road Association 1996).

Sixteen 13 mm diameter deformed bars with a nominal strength of 295 MPa (SD295A) were provided for longitudinal reinforcements, and 6 mm diameter deformed bars (SD295A) were provided at every 500 mm interval for ties. The tie bars were anchored using 135 degree bent hooks with a development length of 100 mm. Longitudinal reinforcement ratio is 1.27 % and the tie volumetric reinforcement ratio is 0.79 %. Concrete strength ranged from 26.2 to 31.3 MPa .

**Loadings**

Cyclic and hybrid loading tests were conducted on 5 and 6 specimens, respectively at the Tokyo Institute of Technology. Under a constant vertical load of 160kN which resulted in 1 MPa compression stress in the columns, the columns were loaded in the unilateral and bilateral directions. Three actuators were used to impose the lateral and vertical loads.



(a) Unilateral (b) Diagonal (c) Square (d) Circular (e) Ellipse

Fig. 2 Bilateral Orbits

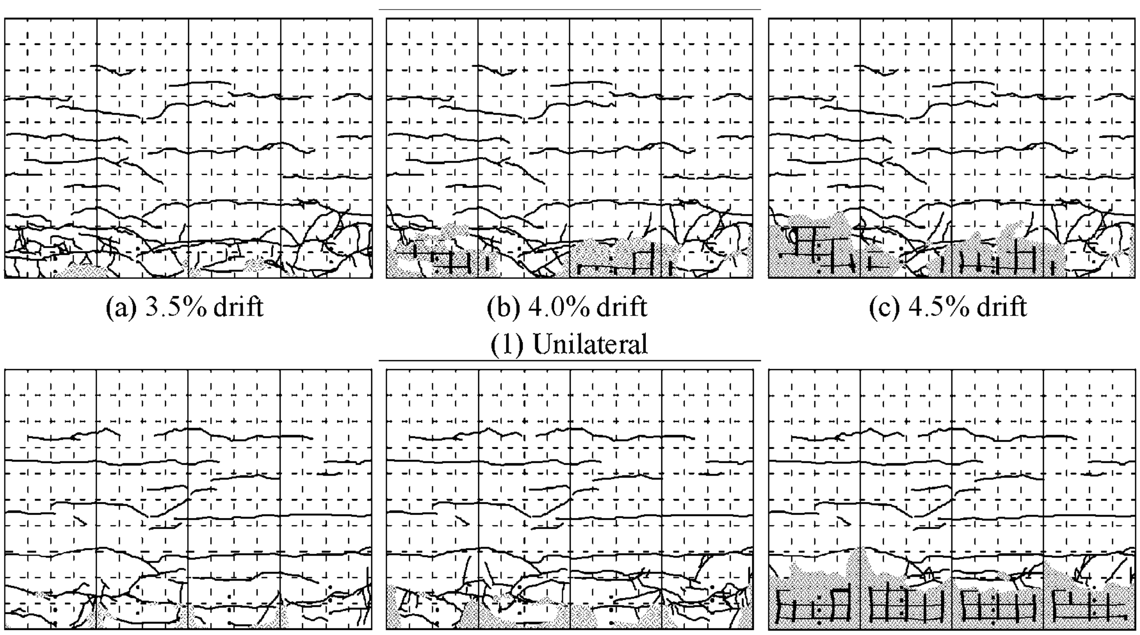
In the cyclic loading test, as shown in Fig. 2 the columns were loaded unilaterally or bilaterally using diagonal, square, circular, and ellipsis orbits of two lateral components under displacement control. Because of limitation of space, only the results under unilateral and circular-orbit loadings are shown here. In the unilateral loading, loading displacement was stepwisely increased from 0.5 % drift until failure with an increment of 0.5 % drift. Since 1 % drift is equal to 13.5 mm, it corresponds to approximately 3 times the yielding displacement. The columns were loaded three times at each loading displacement. In the circular orbit loading, a column was first loaded in the NS direction until the displacement reaches 0.5% drift. From this point the column was loaded three times following the circular orbit. Finally the column was unloaded to the rest position in the NS direction. This set of loadings was repeated until failure with an increment of loading displacement of 0.5 % drift.

In the hybrid loading, the ground accelerations measured at JMA Kobe Observatory during the 1995 Kobe, Japan earthquake and Sylmar Parking Lots during the 1994 Northridge, USA earthquake were used. NS component of the ground accelerations was imposed to the columns in NS direction (refer to Fig. 1) in the unilateral excitation, and both NS and EW components were imposed to the columns in NS and EW directions, respectively, in the bilateral excitations. Intensity of the accelerations was reduced to 30% and 40% of original in the Kobe record, and 50% of original in the Sylmar record. This is because the tributary mass of deck was assumed 50t which is 3.1 times larger than the mass assumed in design. They are called hereinafter 30% Kobe, 40% Kobe and 50% Sylmar records, respectively.

A time-step numerical integration scheme which avoids displacement overshooting using a displacement reduction factor is employed in the simulation system (Shing et al 1991). The P-Δ action of actuators was included in the numerical integration of the equations of motion in the hybrid loading test (Nagata et al 2004). Damping ratio of 2% of critical was assumed in the numerical integration of equations of motion in the hybrid loading test. The time increment was set 0.01 second.

## CYCLIC LOADING TEST

Fig. 3 shows progress of failure of the columns in the cyclic loading test. Under the unilateral excitation, spalling-off of covering concrete occurred in the plastic hinge at 3.5% drift at N and S-surfaces. This further progressed at 4% drift, and a part of the core concrete started to suffer damage at the corner between S and E-surfaces. Eight longitudinal bars suffered local outward buckling at S and E-surfaces. On the other hand, damage of covering concrete started to progress from four corners to the surfaces under the bilateral loading. Not only four corners but also four surfaces suffered extensive damage at 2.5% drift. Longitudinal bars were exposed with the covering concrete being completely spalled-off at 3.5% drift, which resulted in extensive deterioration of restoring force of the column after 3.5% drift.



(a) 3.5% drift (b) 4.0% drift (c) 4.5% drift

(1) Unilateral

(a) 2.0% drift (b) 2.5% drift (c) 3.5% drift

(2) Circular

Fig. 3 Failure Modes under Cyclic Loadings

Fig. 4 shows the lateral force vs. lateral displacement hystereses. Under the unilateral loading, the column yielded at about 1% drift, and maintained the restoring force of about 110kN until 3.5% drift. Because the extensive failure of covering concrete as well as the

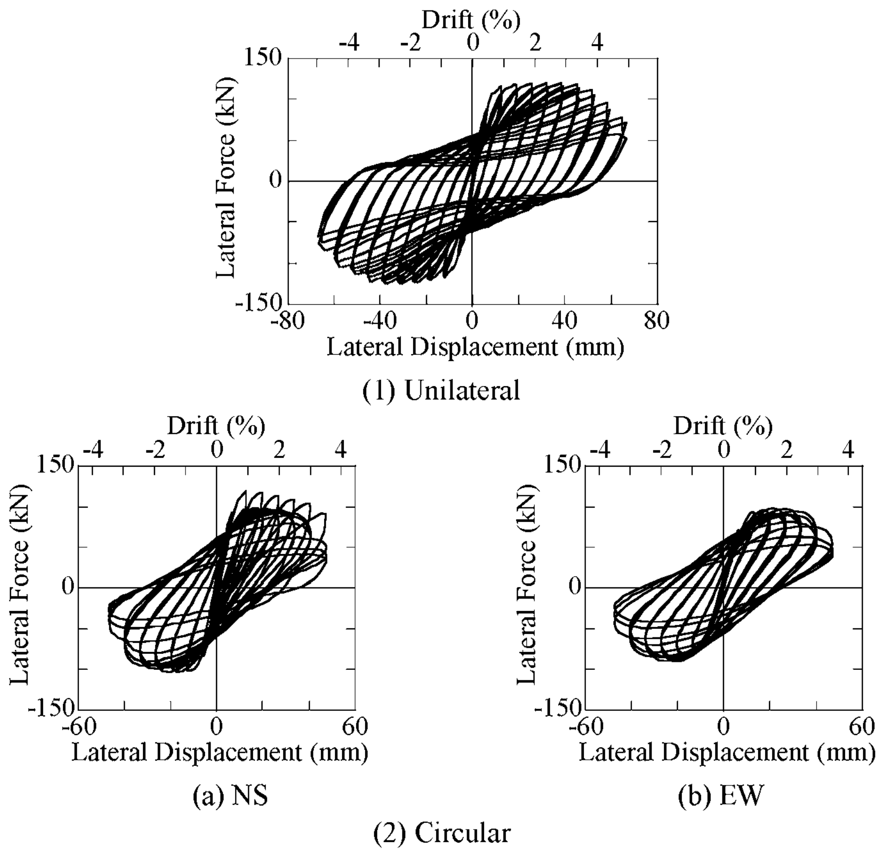



Fig. 4 Lateral Force vs. Lateral Displacement Hystereses under Cyclic Loadings

local buckling of longitudinal bars occurred at 4% drift, this resulted in apparent deterioration of the restoring force at 4% drift. The strength of column was 119.8 kN and 124.5 kN in the positive and negative directions with the averaged strength of 122.3 kN.

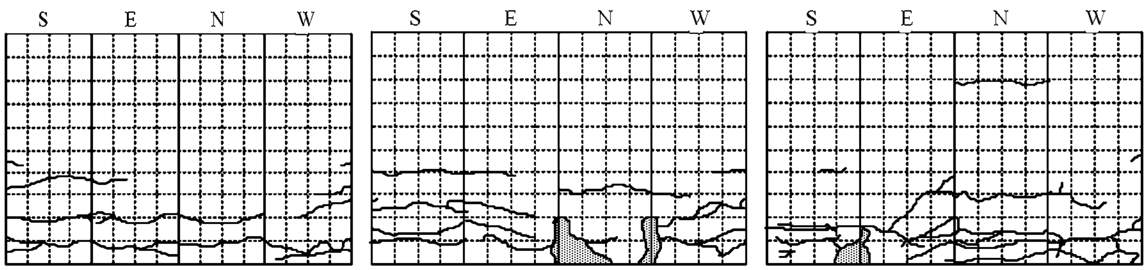
On the other hand, the loading and unloading hystereses are round near the peak displacements under the bilateral loading. This results from the interaction of restoring force in two directions. Only the hystereses at the first excursions in each loading step have a feature similar to that under the unilateral loading. This is because under the circular-orbit loading the column was first loaded only in the N direction in the first excursions at each loading step (refer to Fig. 2). The strength of the column was 103.1 kN and 98.7 kN in the positive and negative directions, respectively, with the average strength of 100.9 kN in the NS directions, while it was 100.6 kN and 88.3 kN in the positive and negative directions, respectively, with the averaged strength of 94.5 kN in EW direction.

Comparing to the strength of the column under bilateral hybrid loading, the strength of the column under bilateral cyclic loading is 14-23% and 15-35% smaller in NS and EW directions, respectively. Furthermore, deterioration of lateral restoring force is significant after 3% drift, while deterioration did not occur within the peak drift of 6.3% under the bilateral hybrid loading.

## HYBRID LOADIUNG TESTS

### Unilateral Excitation

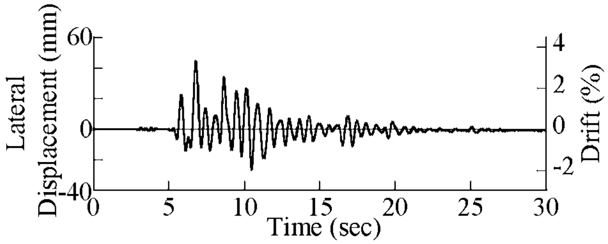
Fig. 5 shows failure modes of the columns under unilateral excitation on the hybrid loading test. The columns suffered several flexural cracks under the 30% Kobe loading, and spalling-off of covering concrete under 40% Kobe and 50% Sylmar loadings.



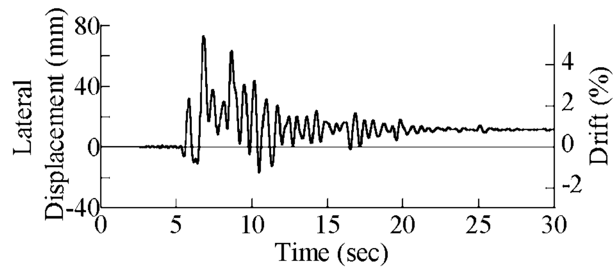

(a) 30% Kobe (b) 40% Kobe (c) 50% Sylmar

Fig. 5 Failure Modes after the Unilateral Hybrid Loading

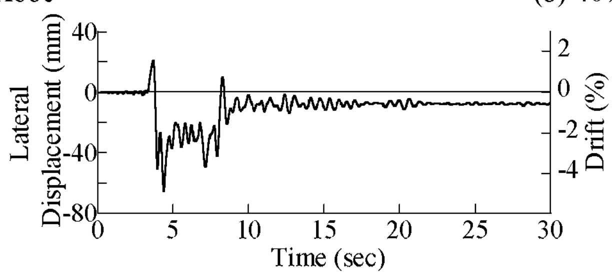
Figs. 6 and 7 show the response displacements and lateral force vs. lateral displacement hysteresis, respectively, at the loading height. The peak drift was 3.4%, 5.4% and 4.8% under the 30% and 40% Kobe and 50% Sylmar excitations, respectively. Residual drift after an excitation was minor (0.062% drift) under the 30% Kobe excitation, while it was 0.86% and 0.54% drift under the 40% Kobe and 50% Sylmar loadings. It is apparent that residual drift after an excitation increases as the intensity of ground motion increases. Although the response displacement was almost symmetrical under the 30% Kobe loading, it biased in the positive and negative directions under the 40% Kobe and 50% Sylmar loadings, respectively. The strength of column was 135.0-141.6 kN under unilateral excitation.




(a) 30% Kobe

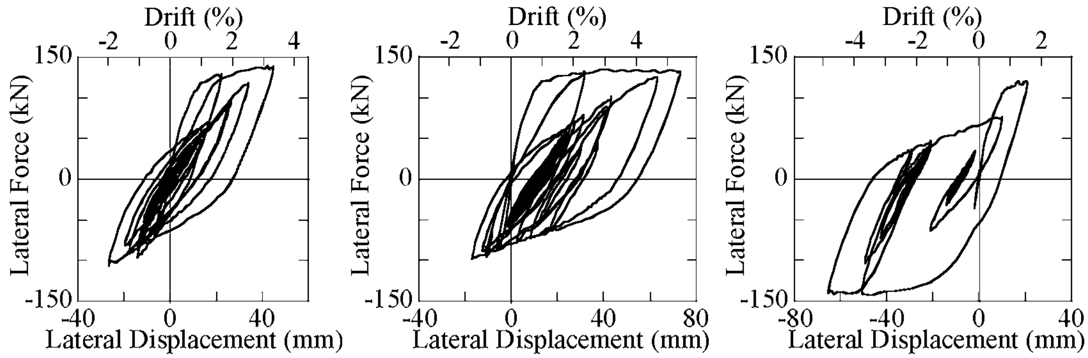



(b) 40% Kobe




(c) 50% Sylmar

Fig. 6 Response Displacements under Unilateral Loading

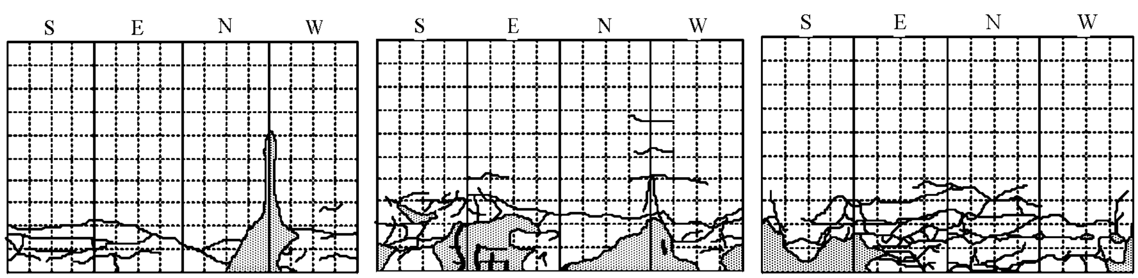



(a) 30% Kobe (b) 40% Kobe (c) 50% Sylmar

Fig. 7 Lateral Force vs. Lateral Displacement Hystereses under Bilateral Loadings

## Bilateral Excitation

Fig. 8 shows the failure modes under the bilateral hybrid loadings. Failure progressed from the corners to middle of the surfaces under the bilateral excitation. Three columns suffered extensive spalling-off of the covering concrete. Comparing Fig. 8 to Fig. 5, it is obvious that the damage was more progressed under the bilateral excitation than the unilateral excitation. Most extensive damage occurred in the column under 40% Kobe loading. Not only covering concrete but also a part of the core concrete suffered damage at the corner of S and W-surfaces. Local buckling of the longitudinal bars occurred at this corner. It is noted that no obvious buckling of bars was not observed in other tests.




(a) 30% Kobe (b) 40% Kobe (c) 50% Sylmar

Fig. 8 Failure Modes after the Bilateral Hybrid Loadings

Figs. 9 and 10 show lateral response displacements and lateral force vs. lateral displacement hystereses of the columns at the loading height. The peak response displacement in NS direction is 4.3%, 6.3 and 5.5 % drifts under the 30% and 40% Kobe and 50% Sylmar loadings, respectively, which are 26.5%, 16.7% and 14.6%, respectively, larger than the peak response displacements under the unilateral loadings. It is also noted that the flexural strength of the columns in NS direction was 115.2kN, 118.6kN and 123.7kN under 30% and 40% Kobe and 50% Sylmar loadings, respectively. They are 17.4%, 13.8% and 12.6% smaller than the respective strength under the unilateral loadings. As is apparent in Figs. 5 and 8, more extensive damage of the columns occurred under the bilateral loadings which resulted in larger deterioration of the flexural strength in NS direction. This, in turn, resulted in larger response displacement of the column in the same direction under the bilateral loading.

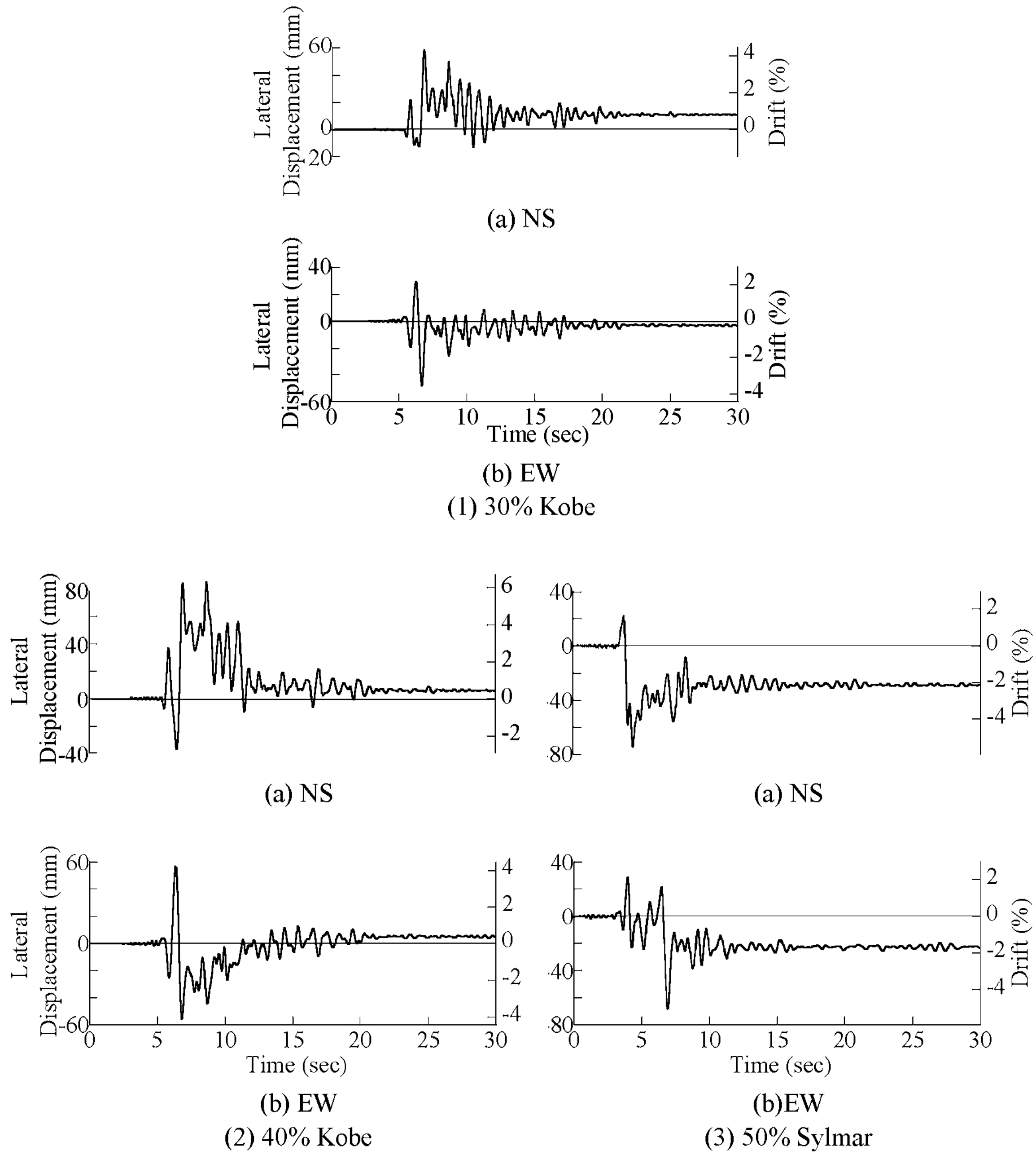



Fig. 9 Response Displacements under Bilateral Loadings

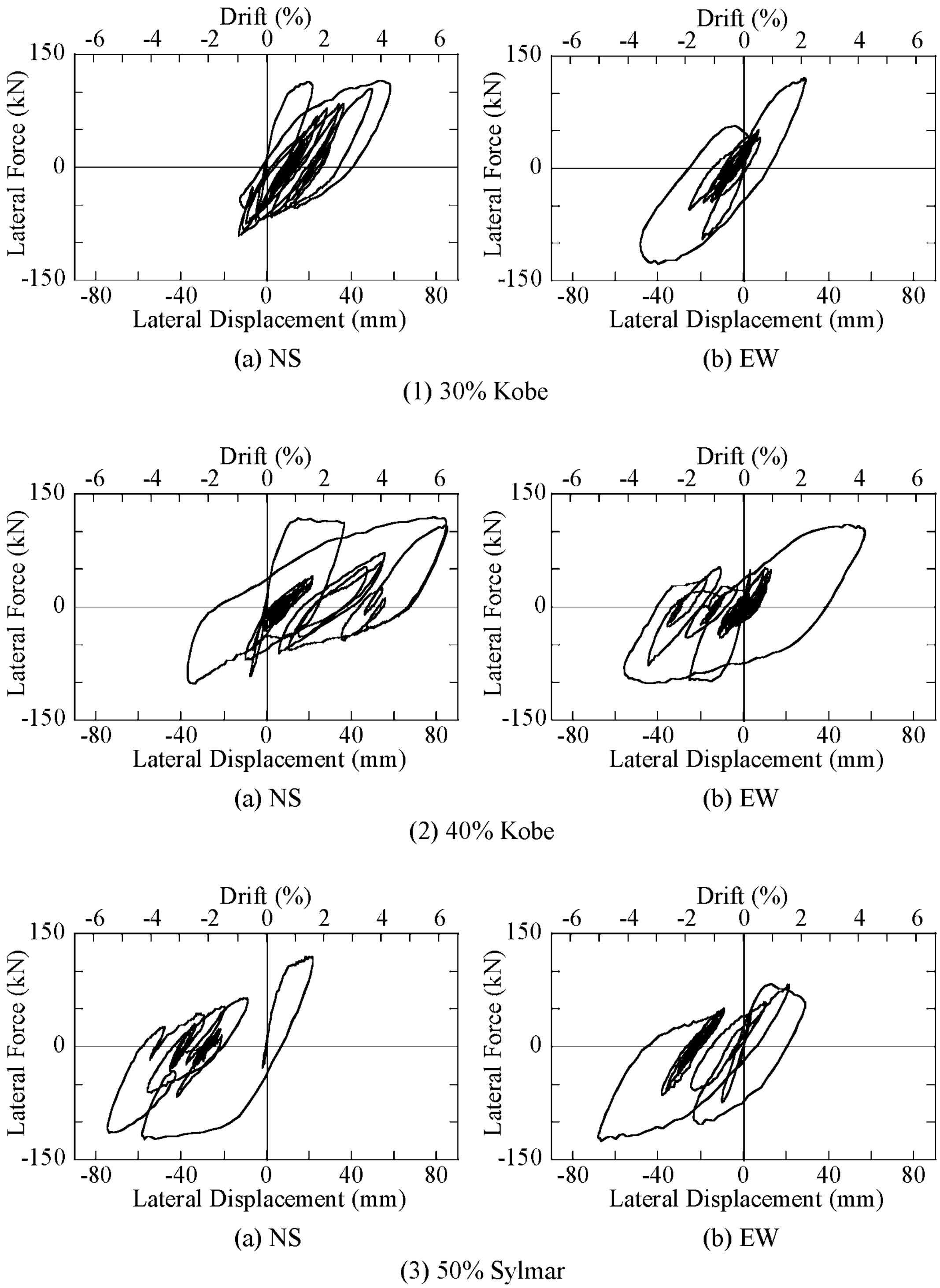



Fig. 10 Lateral Force vs. Lateral Displacement Hystereses under Bilateral Loadings

## FIBER ELEMENT ANALYSIS

### Analytical Model

The columns were modeled as shown in Fig. 11. The plastic hinge zone was idealized by a fiber element. The effect of deformation of longitudinal bars in the footing was represented by a rotational spring at the bottom of the columns. The stress $\sigma_c$ vs. strain $\varepsilon_c$ relation of the confined concrete was assumed based on Hoshikuma et al (Hoshikuma et al 1997). Unloading and reloading hystereses were idealized based on a model by Sakai and Kawashima (Sakai and Kawashima 2000). This model idealizes a comprehensive stress vs. strain relation under various combinations of full unloadings and reloadings, and partial unloadings and reloadings. Accumulation of plastic strains and deterioration of unloading stress under cyclic unloading and reloading process are included in the model as shown in Fig. 12.

On the other hand, the Menegotto-Pinto model (Menegotto and Pinto 1973) was used to idealize the stress vs. strain hysteresis of the axial bars.

Damping ratio of 0.02 was assumed for 1st and 2nd modes in the analysis in terms of Raylegh damping.

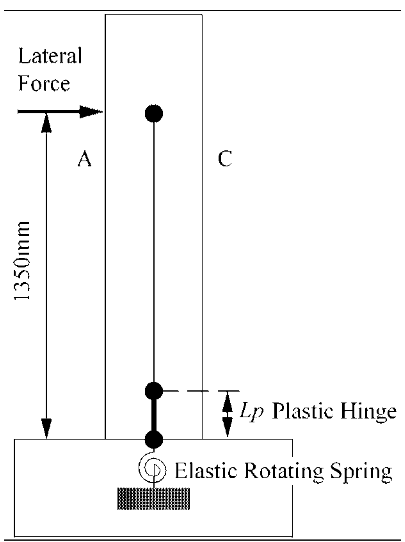



Fig. 11 Analytical Model

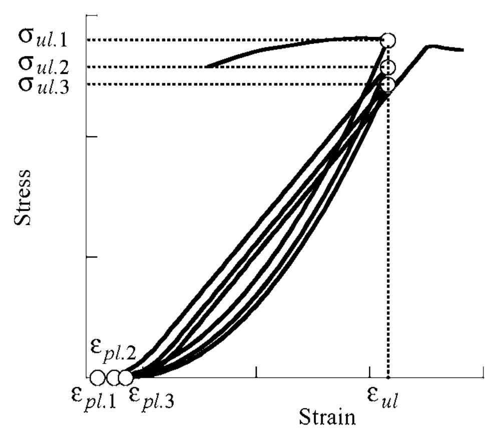



Fig. 12 Unloading and Reloading Model of Confined Concrete

### Analytical Correlations

Fig. 13 compares the lateral force vs. lateral displacement hystereses between the experiment and the analysis in the first loading excursion of 1%, 2% and 3% drifts on the columns subjected to bilateral cyclic loadings. The computed hystereses agree well with the experimental results.

Figs. 14 and 15 compare the computed response displacements and lateral force vs. lateral displacement hysteresis, respectively, to the experimental results on the columns subjected to the bilateral hybrid loadings. Again, the overall responses are well predicted by the analysis. However residual drifts are less accurately correlated by analysis on the

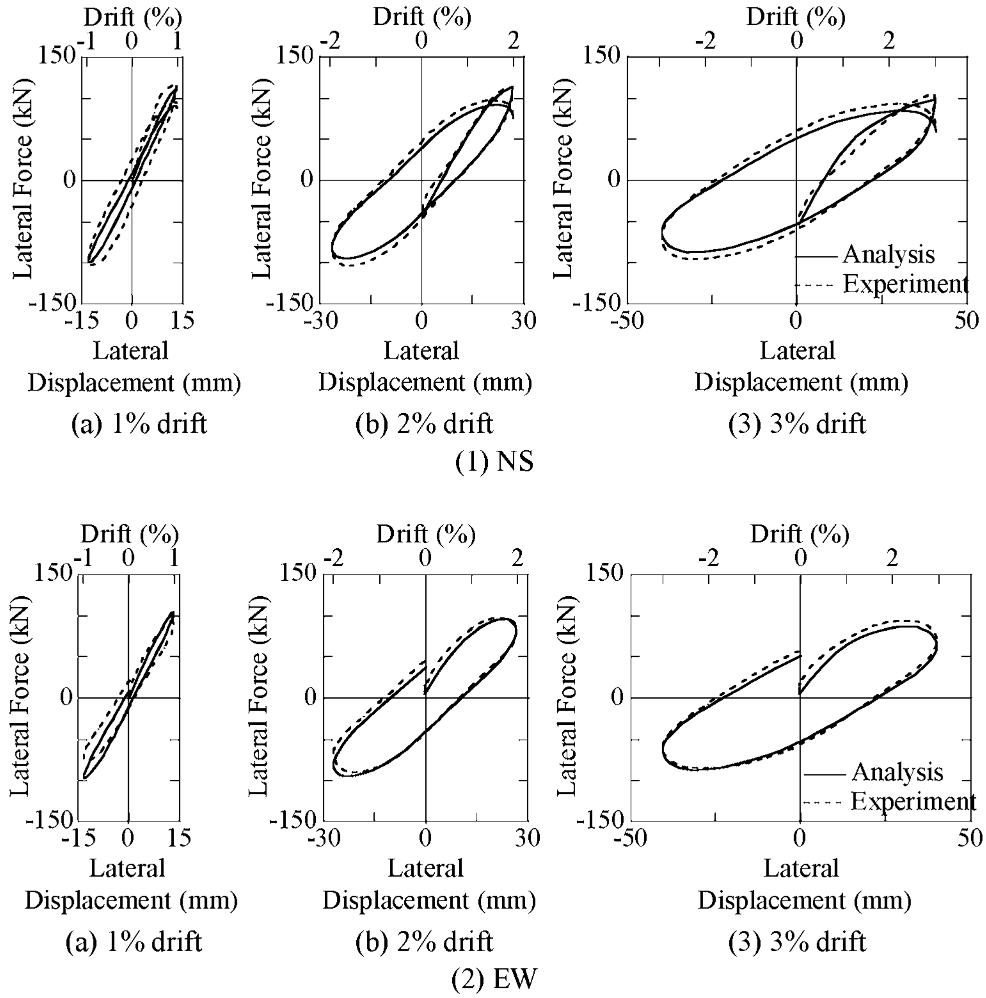



Fig. 13 Comparison of Analytical and Experimental Hystereses at 1%, 2% and 3% Drifts under Circular-Orbit Loadings

column subjected to 50% Sylmar record. Since residual drifts are sensitive to the post-yield stiffness (Kawashima et al 1998), it is needed to accumulate more experience for the correlation.

## CONCLUSIONS

Cyclic and hybrid loading tests were conducted on eleven cantilevered reinforced concrete bridge columns with a 400 mm x 400 mm square section. Fiber element analysis was conducted to correlate the experimental response. Based on the experimental and analytical results presented

1) Flexural strength and ductility capacity of reinforced concrete bridge columns with a square section significantly deteriorate under the bilateral excitation than unilateral excitation in both cyclic and hybrid loading tests.

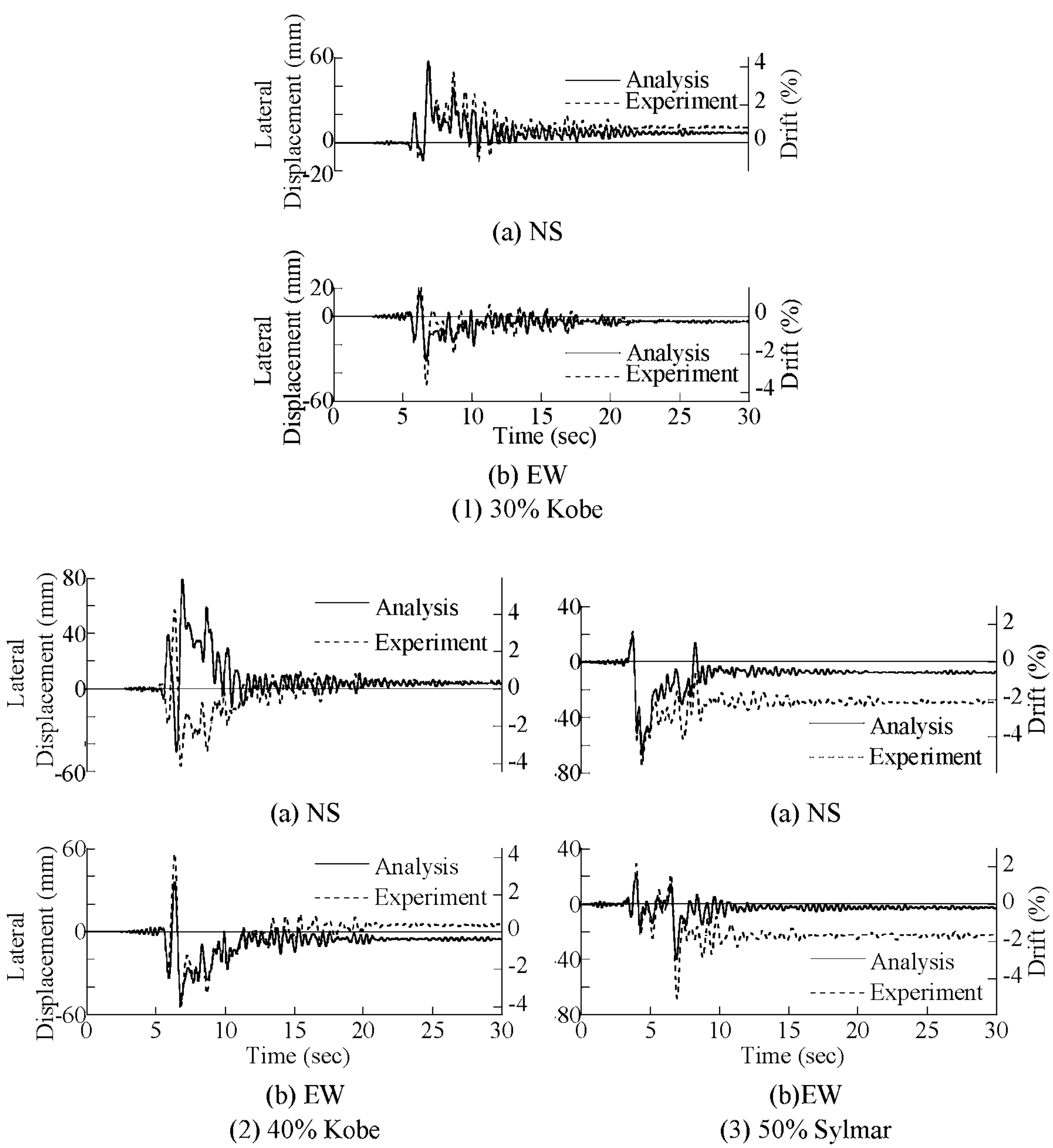



Fig. 14 Computed Response Displacements of the Columns under Bilateral Excitation

2) Failure of the columns under the cyclic loading test in which loading displacement was stepwisely increased with three loading excursions at each loading step is much extensive than the failure developed in the hybrid loading test using the JMA Kobe Observatory ground motion in the 1995 Kobe, Japan earthquake and the Sylmar Parking Lots ground motion in the 1994 Northridge, USA earthquake. Loading protocol is important, and it has to be carefully determined in the cyclic loading tests.
3) The 40% Kobe record and the 50% Sylmar record result in similar peak response displacements in the bilateral hybrid loading tests. However, residual drift is much larger in both NS and EW directions under the 50% Sylmar than the 40% Kobe records. The residual drift highly depends on ground motions.

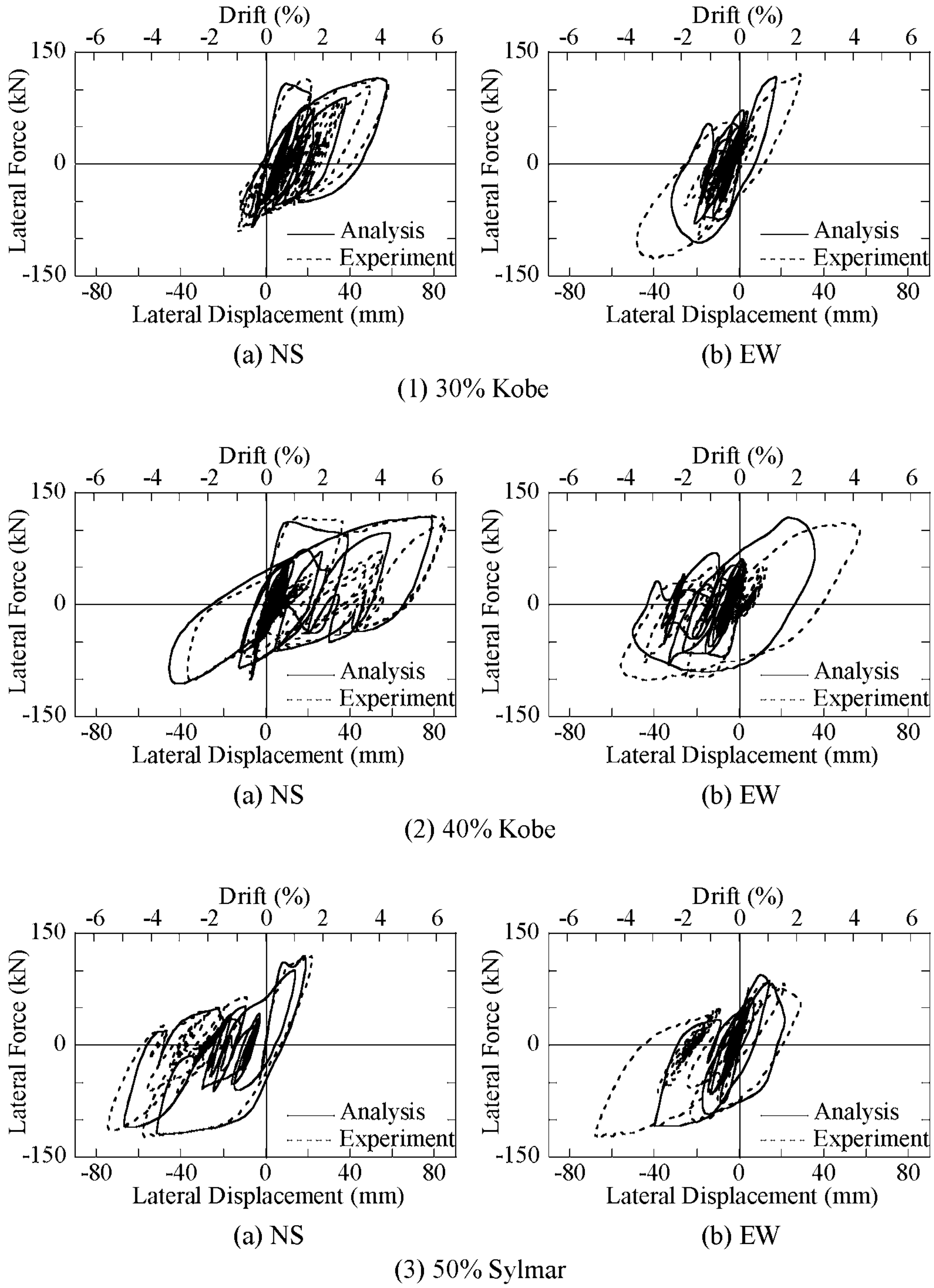



Fig. 15 Lateral Force vs. Lateral Displacement Hystereses of the Columns under Bilateral Excitation

4) Analytical model provides quite accurate lateral force vs. lateral displacement hystereses of the columns in the cyclic loading tests. Overall response of the columns in the hybrid loading tests can be correlated by analysis. However evaluation of residual drifts requires more experience in the analysis because it is sensitive to the post-yield stiffness.

## ACKNOWLEDGMENT

The authors express their sincere appreciation to Dr. Yabe, M., Chodai Consultants, for design of the model columns, and Dr. Sakai, J., University of California, Berkeley, for use of the confined model of concrete. Extensive support was provided by Messrs. Nagata, S., Nakamura, G., Fukuda, T., Ichikawa, Y., Miyaji, K. and Kijima, K. for constructing specimens and conducting the test.

## REFERENCES

Hayakawa, R., Kawashima, K., Watanabe, G.. (2004). "Effect of bilateral excitation on the flexural strength and ductility capacity of reinforced concrete bridge columns," *Journal of Structural Mechanics and Earthquake Engineering*, JSCE, 759/I-67, 79-98.

Hoshikuma, J., Kawashima, K., Nagaya, K. and Taylor, A. W. (1997). "Stress-strain model for confined reinforced concrete in bridge piers," *Journal of Structural Engineering*, ASCE, 123(5), 624-633.

Japan Road Association (1996). "Part V seismic design, design specifications of highway bridges," Maruzen, Tokyo, Japan.

Kawashima, K. and Hasegawa, K. (1992). "Effect of bilateral loading on dynamic strength and ductility of reinforced concrete bridge piers," *Civil Engineering Journal*, 37(7), 38-43.

Kawashima, K. MacRae, G. Hoshikuma, J. and Nagaya, K. (1998). "Residual displacement response spectrum." *Journal of Structural Engineering*, ASCE, 124(5), 523-530.

Kawashima, K., Watanabe, G. and Hayakawa, R. (2003). "Seismic performance of reinforced concrete bridge columns subjected to bilateral excitation," *Proc. 35th Joint Meeting, Panel on Wind and Seismic Effects, UJNR*, 193-207, Public Works Research Institute, Tsukuba Science City, Japan

Menegotto, M.and Pinto, P.E. (1973). "Method of analysis for cyclically loaded R.C. plane frames including changes in geometry and non-elastic behavior of elements under combined normal force and bending," *Proc. IABSE Symposium on Resistance and Ultimate Deformability of Structures Acted on by Well Defined Repeated Loads*, pp.15-22.

Nagata, S., Kawashima, K., Watanabe, G. (2004). "Effect of P-Δ action of actuators in a hybrid loading test." *Proc. 13th World Conference on Earthquake Engineering*, Vancouver, Canada.

Sakai, J. and Kawashima, K. (2000). "An unloading and reloading stress-strain model for concrete confined by tie reinforcements," *Proc. 12th World Conference on Earthquake Engineering*, CD-ROM, No. 1432, Auckland, New Zealand.

Shing, P, B., Vannan, M.T. and Cater, E.(1991), "Implicit Time Integration for Pseudodynamic Tests," *Earthquake Engineering and Structural Dynamics*, Vol. 20, 551-576.

Zahn, F. A., Park, R., and Priestley, N. M. J. (1983). "Strength and ductility of square reinforced concrete column sections subjected to biaxial bending," *ACI Structural Journal*, 56(2), 123-131,1983